

Tools for Drell-Yan at NNLO

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Drell-Yan at LHC

- neutral current Z production has large σ
 - clear collider signature with l^+l^-
- LHC standard candle
 - detector calibration
 - luminosity monitoring (Dittmar et. al.)
 - measure EW parameters
 - PDF measurements

DY at NNLO?

- LHC will produce large amount of data
 - small statistical error
 - measurements limited by systematics & theoretical error
- Can expect percent level physics
- Need to understand distributions, backgrounds, uncertainties
 - measurements require theory input
 - need higher order calculations

Need for Differential Distributions

- DY at NNLO calculated, but inclusive (Hamberg, Matsuura, van Neerven)
- differential distributions needed
 - PDF extraction Z rapidity dependent
 - simulate distributions in detector-like scenarios
 - > cuts on p_T , rapidity, isolation
- 2006: FEWZ (Melnikov, Petriello)
 - compute W/Z DY cross sections in hadron colliders
 - > Fully Exclusive at LO, NLO, & NNLO in QCD
 - > Leptonic decays of W & Z contain full spin correlations

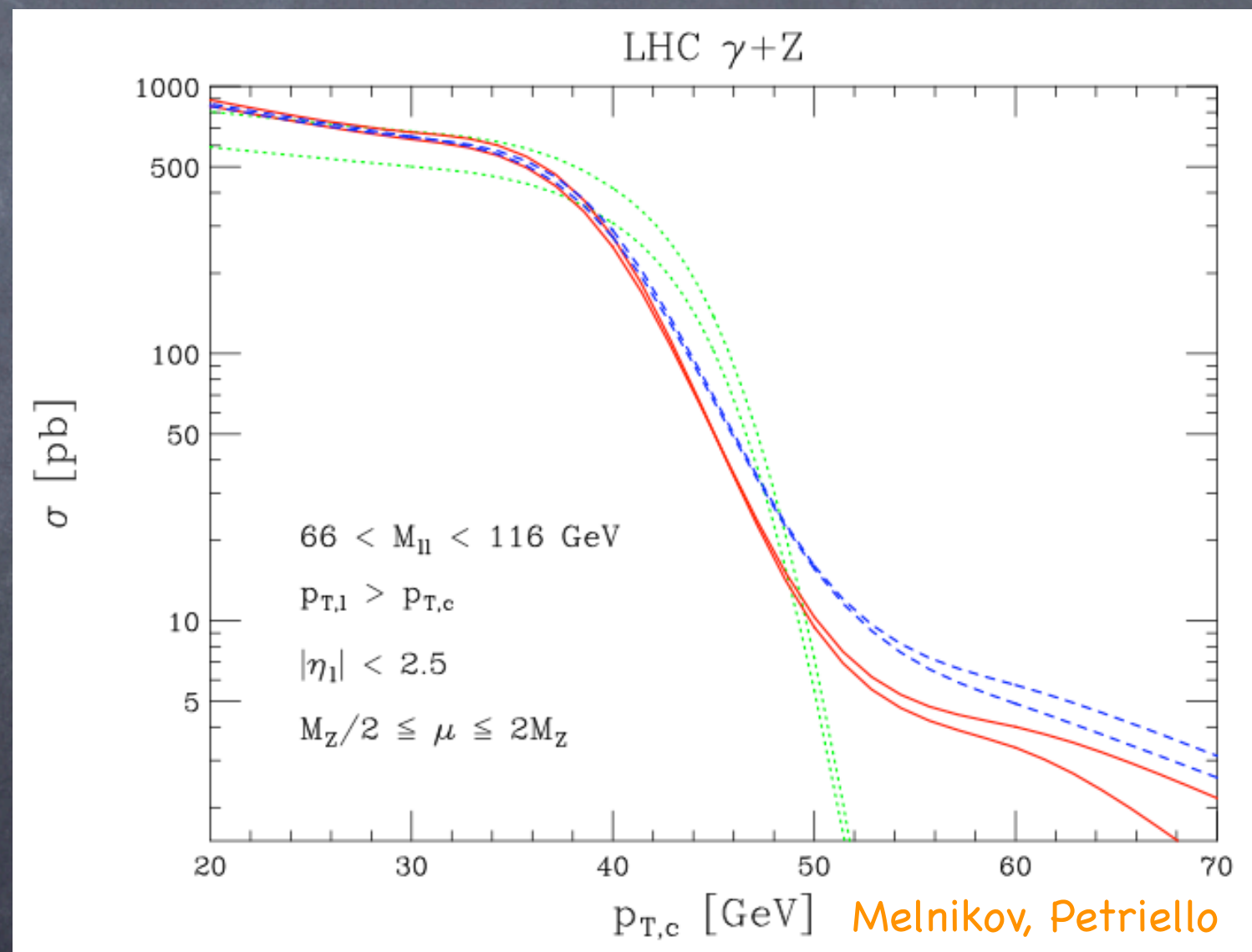
FEWZ

- Fortran based numerical code which allows user to control DY calculation:
 - two executables: FEWZw & FEWZz, for charged and neutral current DY production respectively
 - perturbative order in QCD & CM energy
 - collider type (pp or $p\bar{p}$)
 - numerical integration parameters (Vegas)
 - PDF set (CTEQ & MRST/MSTW)
 - cuts on leptons

FEWZ

- Example: $\sigma_{Z \rightarrow l^+ l^-}(\text{lepton } p_T \text{ cut})$
- clear discrepancy between NLO & NNLO at high p_T cutoff

- NNLO: blue
- NLO: red
- LO: green



FEWZ

- FEWZ is very useful, but could use improvements
 - can only calculate one number per run
 - lengthy run time for NNLO
 - user must manually hard code cuts
 - some parameters are hard coded (Vegas, EW)
- Changes to some FEWZ parameters require recompiling
- Goal: ease use of FEWZz (neutral current DY) for user

Improved FEWZz

- New features to FEWZz:

- PDF error propagation
- revised input file (set cuts, PDF, jet algorithm, isolation)
- simultaneous generation of predefined histograms
 - > histogram parameters set in a histogram input file
- reduced run time for NNLO calculations

Reduced Run Time at NNLO

- Previous version, entire NNLO expression in integrand
 - large expression for Vegas to integrate
- NNLO expression now sensibly split into 'sectors'
 - each sector integrated separately, then combined later
 - some sectors anti-correlate – recombined before integration – improve convergence and lower χ^2
 - separate sectors can be evaluated in parallel using multiple processors locally, or by using a batch job system (e.g. Condor)

Input File

- Improved input file → improved user interface
 - set CMS collision energy, μ_F & μ_R scales, collider type, EW parameters (couplings, masses, widths)
 - set Vegas parameters (desired accuracy, evaluation, iterations)
 - set desired cuts: invariant lepton mass
Z, lepton, & jet – p_T & rapidity (Y, η)
jet algorithm cone size, ΔR_{algo}
isolation: lep/lep, lep/jet
min & max # of jets allowed in event
 - define desired PDF and related parameters
- These parameters no longer hard coded

Histogram Input File

- Histograms in FEWZz are predefined
 - lepton pair invariant mass
 - Z, lep & jet: pT & rapidity
 - ΔR separation: lep/lep, lep/jet, & jet/jet
 - Collins-Soper related moments (A_i) and angles
- Parameters (for individual histograms) set in histogram input file:
 - lower edge of histogram
 - higher edge
 - # of bins
 - T/F to write histogram to output file

FEWZz at Work

- Study of theoretical uncertainties (Adam, Halyo, Yost)
 - in neutral current DY at LHC – 14 TeV
- FEWZz used to generate numerics for DY at NNLO in QCD
 - 3 kinematic regions

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Cut 1	$40 \text{ GeV} < M_{ll}$	$ \eta_{lep} < 2$	$lep \ p_T > 20 \text{ GeV}$
Cut 2	$40 \text{ GeV} < M_{ll}$	$1.5 < \eta_{lep} < 2.3$	$lep \ p_T > 20 \text{ GeV}$
Cut 3	$79 < M_{ll} < 104 \text{ GeV}$	$ \eta_{lep} < 2$	$lep \ p_T > 20 \text{ GeV}$

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NLO
Adam, Halyo, Yost
Improved FEWZz

$\sigma_{tot} \text{ (pb)}$	2358.1 ± 2.3	2357.5 ± 0.7
$\sigma_{Cut \ 1}$	716.0 ± 0.7	714.4 ± 0.8
$\sigma_{Cut \ 2}$	74.1 ± 0.07	74.18 ± 0.09
$\sigma_{Cut \ 3}$	657.2 ± 0.7	656.6 ± 0.3

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NNLO Adam, Halyo, Yost Improved FEWZz

$\sigma_{tot} \text{ (pb)}$	2334.9 ± 4.6	2331.1 ± 0.8
$\sigma_{Cut \ 1}$	726.2 ± 5.5	719.5 ± 4.1
$\sigma_{Cut \ 2}$	73.39 ± 1.96	75.6 ± 1.1
$\sigma_{Cut \ 3}$	650.4 ± 4.0	656.0 ± 2.8

FEWZz at Work

- Scale variation – μ_R, μ_F
 - contribution to theoretical error in fixed order calculations
- Improved FEWZz → inclusive, NC DY cross section (pb)
 - LHC @ 7 TeV
 $66 < M_{ll} < 116 \text{ GeV}$

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	$\mu_R=\mu_F=M_Z/2$	$\mu_R=\mu_F=M_Z$	$\mu_R=\mu_F=2M_Z$	$\Delta\sigma/\bar{\sigma}$
NLO	920.5 ± 0.1	931.5 ± 0.1	945.6 ± 0.2	$1.51\% \pm 0.02\%$
NNLO	1040.4 ± 0.5	1033.2 ± 0.4	1030.0 ± 0.5	$0.70\% \pm 0.06\%$

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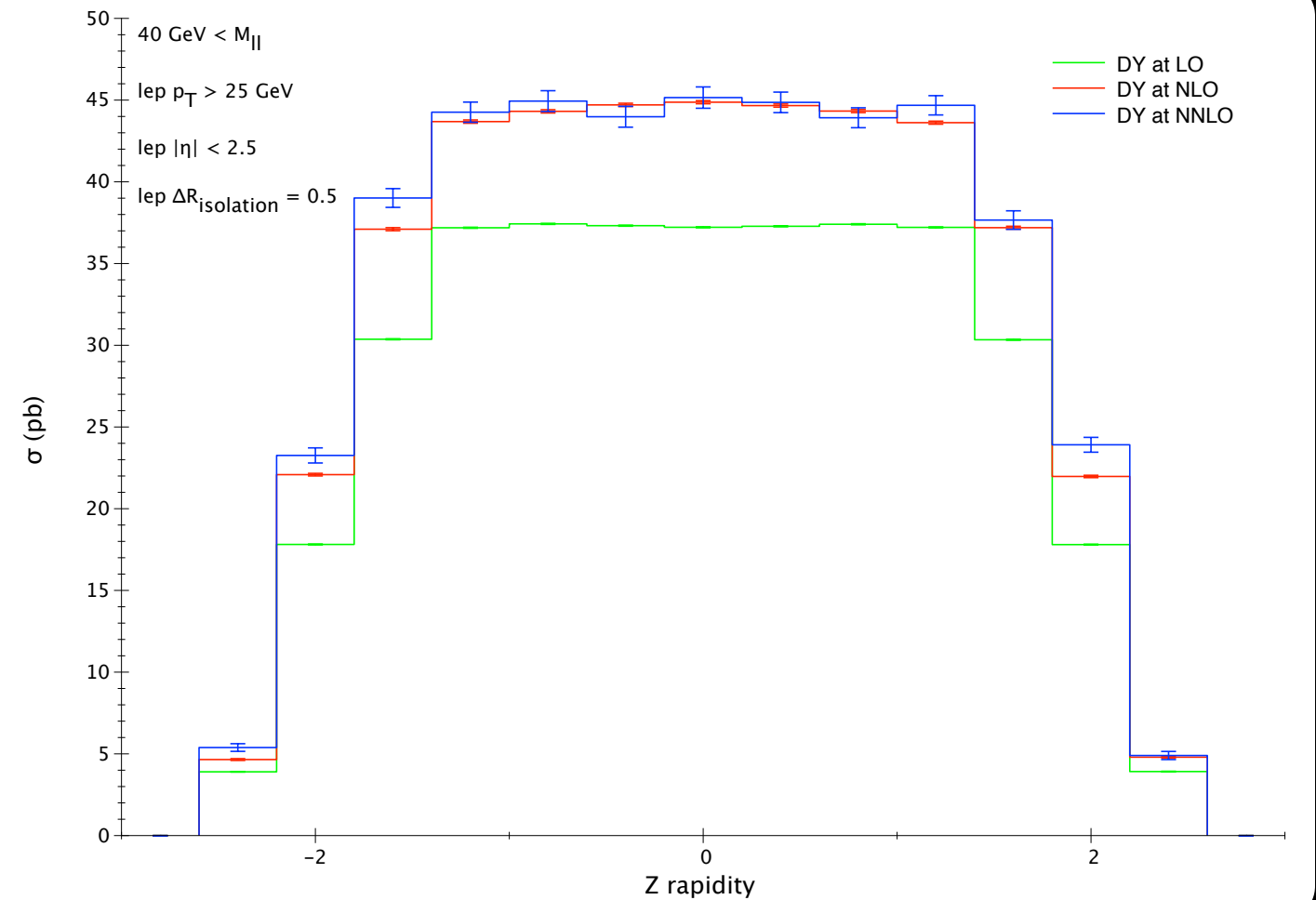
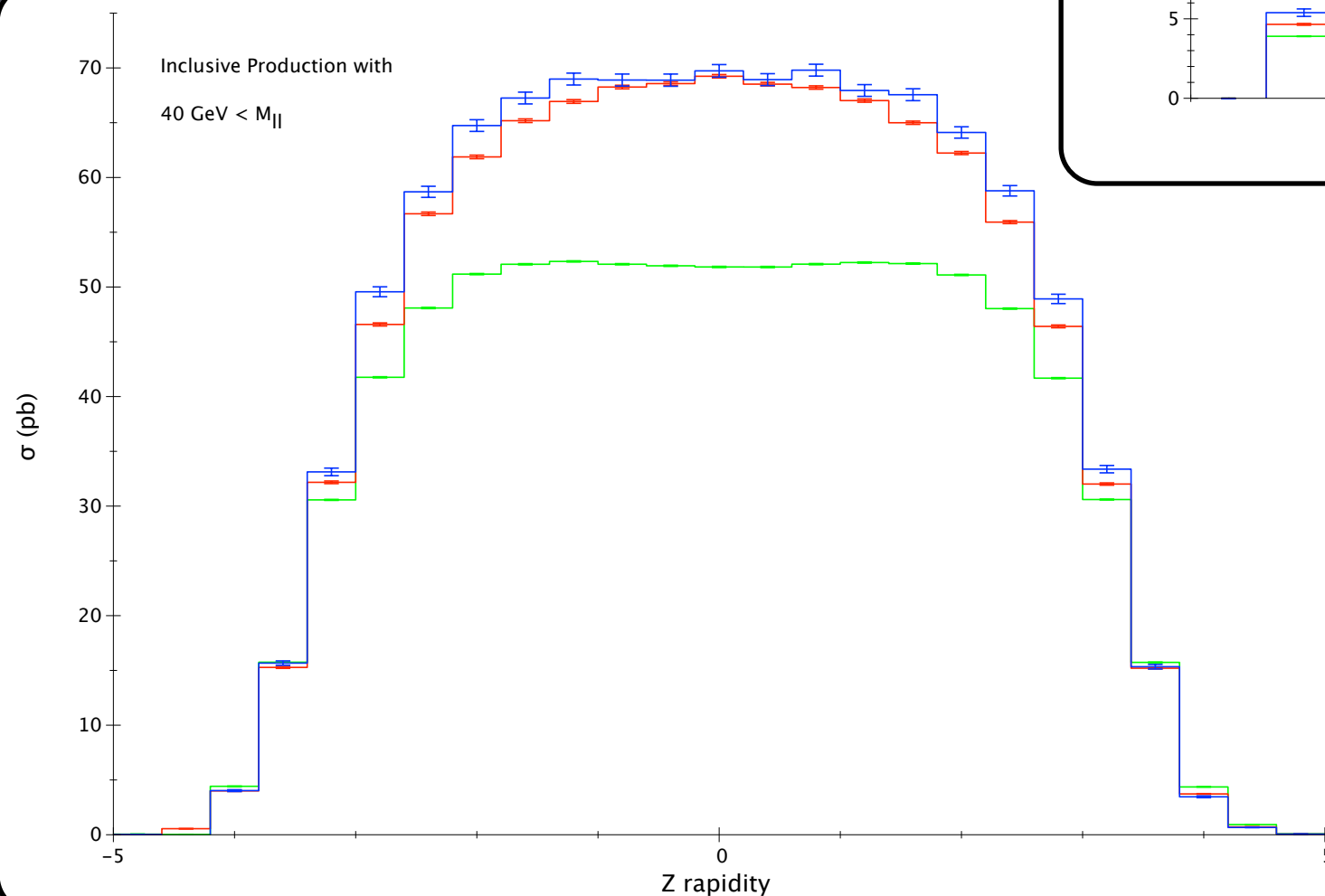
$$\delta_{\text{integration}}/\delta_{\text{scale}} \leq 10\%$$

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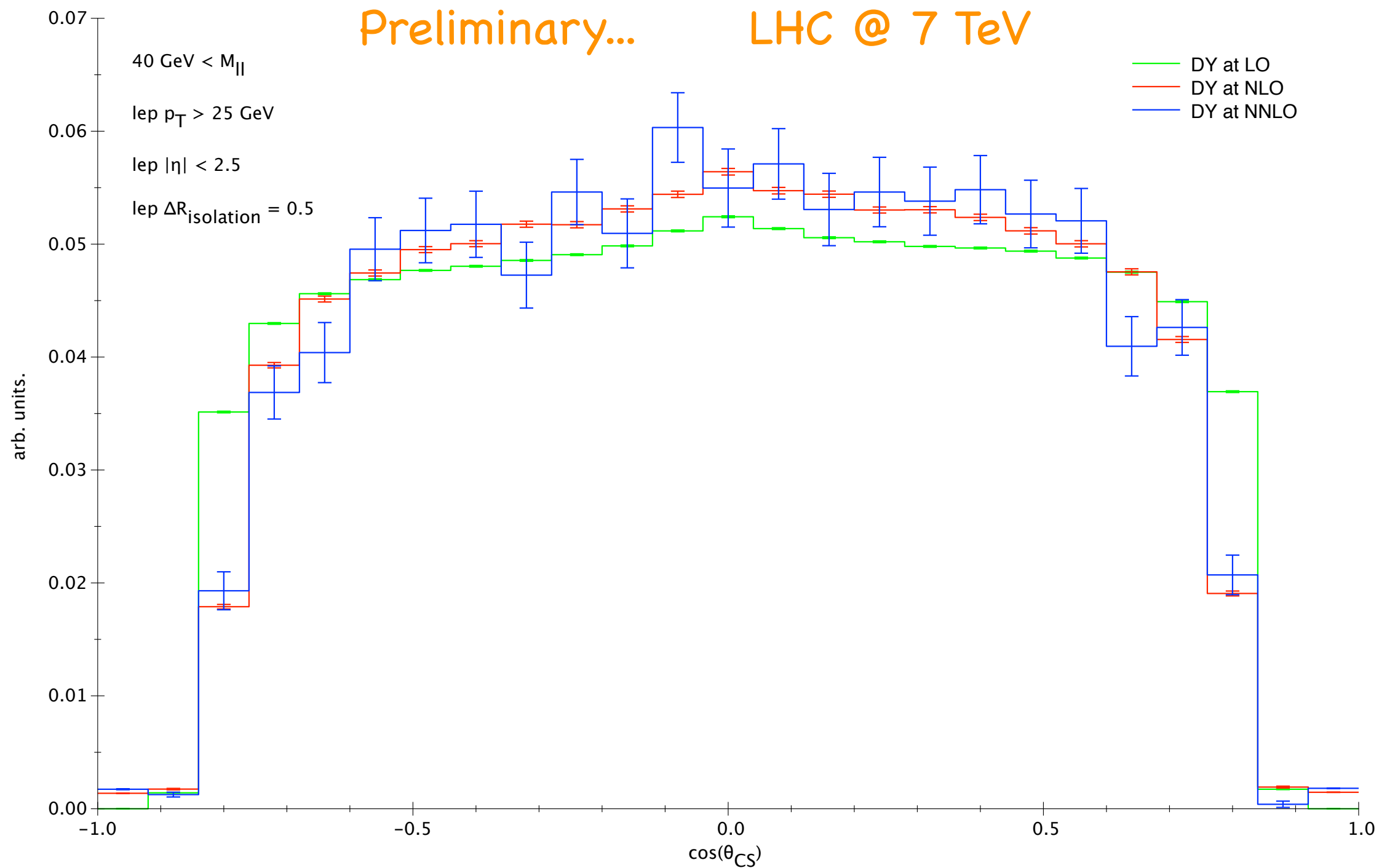
FEWZz at Work

Preliminary...

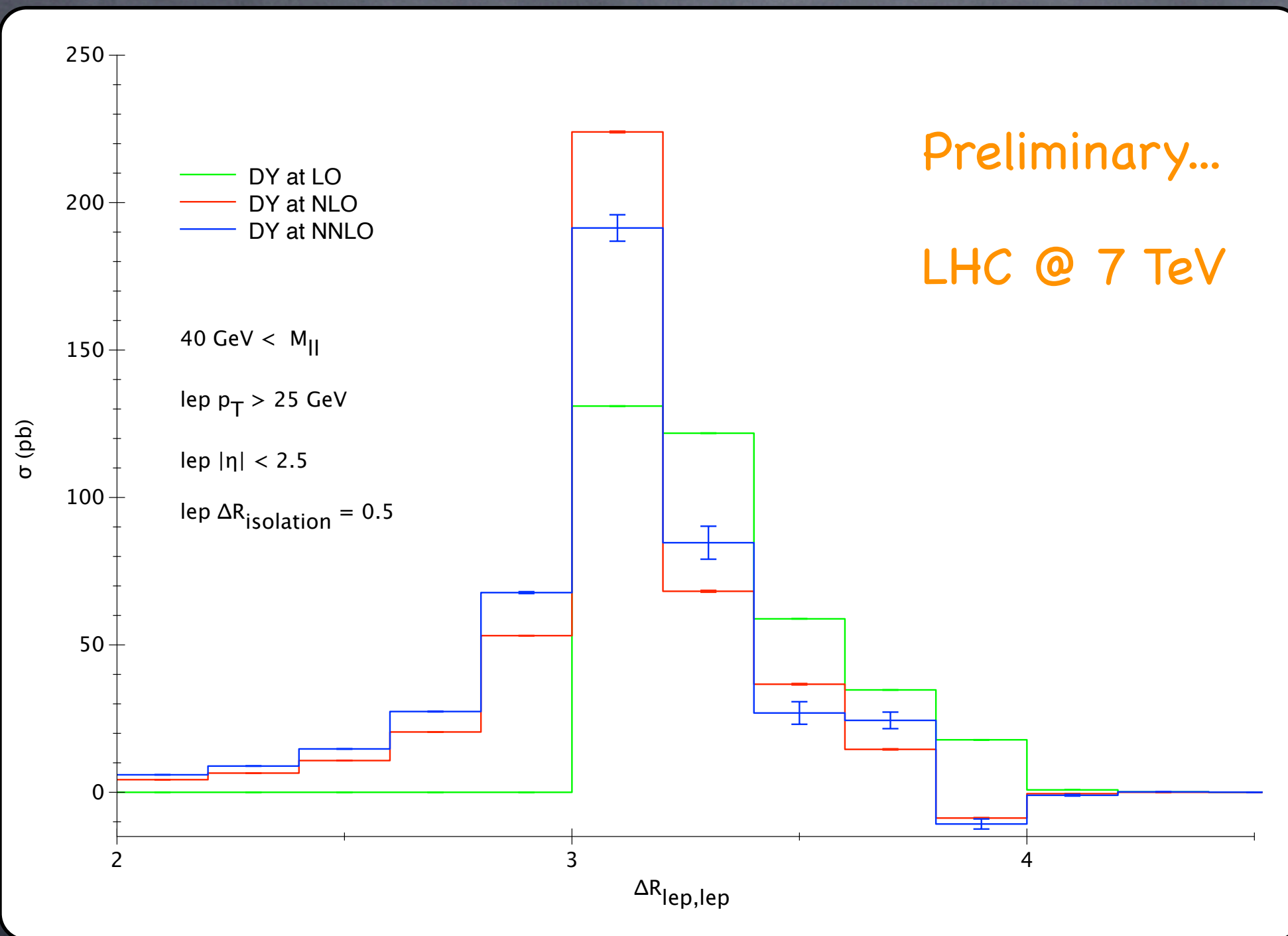
LHC @ 7 TeV



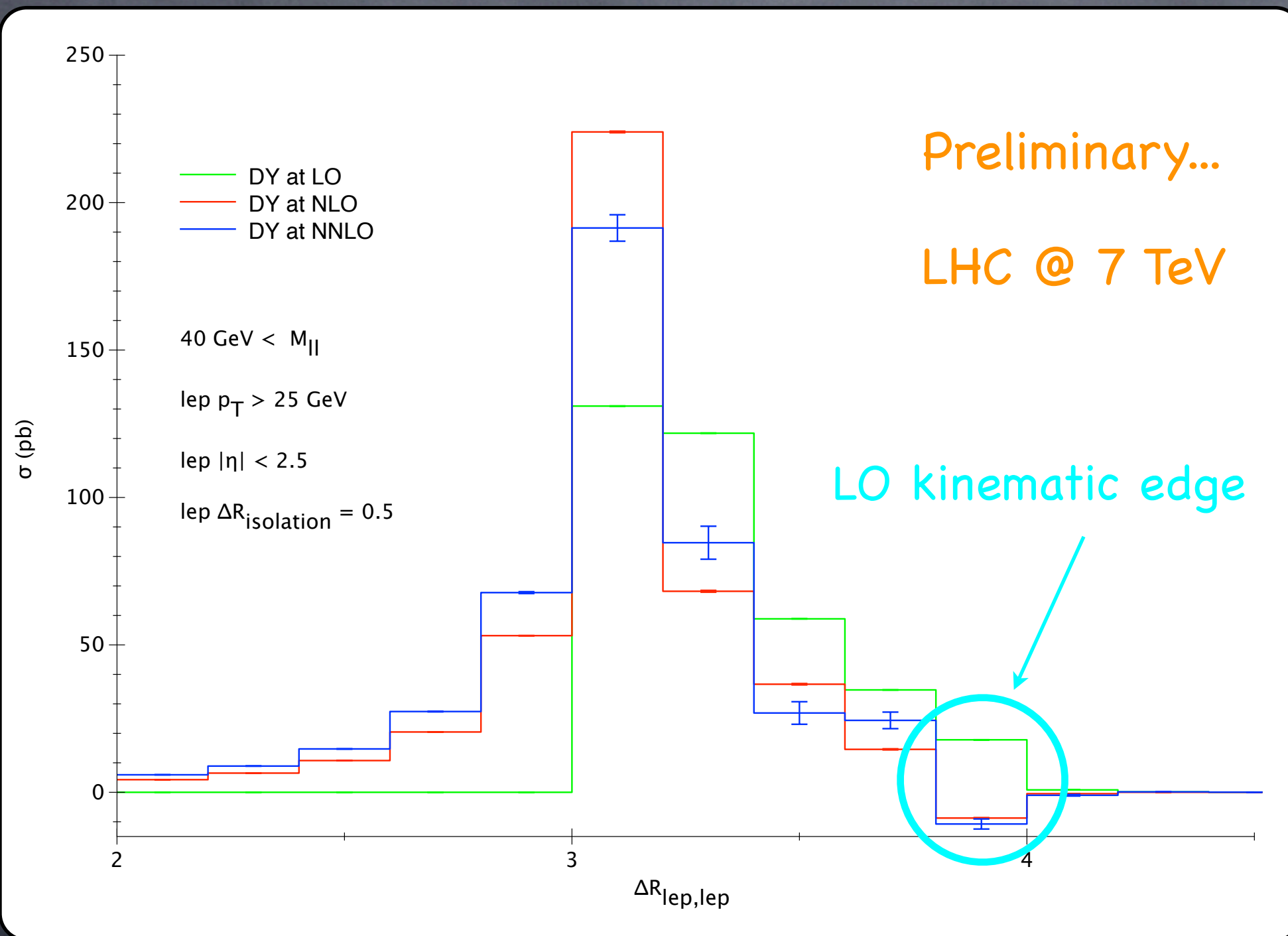
More Distributions



More Distributions



More Distributions



Conclusions

- Drell-Yan is still a very important process at the LHC
 - need higher order calculations
 - NNLO QCD corrections to DY
 - need differential distributions at NNLO
- FEWZ is an excellent tool to study higher order effects, through NNLO QCD, on DY at the differential level
- Updated version of FEWZz to be released soon, with many improvements to usability & functionality
 - EW corrections to come in the near future
- Encourage you to download and try FEWZz, especially when new version released (<http://www.hep.wisc.edu/~frankjp/FEWZ.html>)